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The Feasible Conditions Study of Steamflooding for Heavy Oil Reservoirs In China After Cyclic Steam Injection

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ABSTRACT

China is rich in heavy oil reserves. In recent ten years, the production of heavy oil has rapidly grown through application of steam injection and the annual production reached up to 11.9 million tons in 1993. At present, with the increase of cycles of steam injection, the effectiveness becomes poorer and the challenge of changing steam stimulation into steamflooding has to be confronted. Because of heavy oil reservoirs in China characterized with complex geological conditions, deeply buried, multi-layers and serious heterogeneity, especially some complicated conditions occurring in steam cycling, the effectiveness of steamflooding pilots has not been ideal commonly. Therefore, it is urgent to study and determine the comprenhensive conditions at which the reservoirs are feasible to be converted from steam cycling to steeamflooding at the present technological situation.

In this paper, based on three typical types of heavy oil reservoirs, systemetic studies have been conducted to investigate the effects of oil viscosity, oil formation thickness, vertical permeability difference, reproduction ratio of injected water in steam cycling and channelling path etc. on steamflooding effectiveness. Then, a practical screening criterion of steamflooding is proposed to provide technical bases for the conversion.

References and illustrations at end of paper

INTRODUCTION

The commercial thermal recovery for heavy oil in China started in the late of 70's and the beginning of 80's. Although the conditions of China heavy oil reservoirs are generally not ideal, characterized with many types, most buried deeply (900~1,600m) and complex geology, thermal recovery technology has been developed rapidly in China in the last more than ten years through the advancement of science and technology, and heavy oil production has steadyly increased. As the result, China has became one of the main heavy oil production countries in the world. Now, cyclic steam injection technology has matured and integrated, and been widely applied, as the main method of heavy oil production. Meanwhile, steamflooding pilot test and development test have been under way at various typies of heavy oil reservoirs. Four heavy oil production bases have been set up in Liaohe, Shengli, Xinjiang and Henan oilfields. In 1993, more than 9,000 cyclic steam injection operations had been conducted in about 6,000 wells and more than 200 patterns have been in process of steamflooding. The annual heavy oil production in 1993 and 1994 reached 11.9 million and 12.3 million tons respectively, which accounted nearly 1/10 in the national total oil production.

At present, cyclic steam injection becomes poor with increase of steam injection cycles (Fig. 1). The effective period shorted, OSR declined and economic benefit decreased. According to the statistical data, the cyclic steaming wells above 5 cycles have accounted 36.1% of the total cycling wells, and OSR has been 0.49. Cyclic steam injection has entered into the middle and late stage and faced the challenge of converting to steamflooding. In some reservoirs, the complex problem of low re-production rate of injected steam (or water) appeared (for example, less than 20% in Gao sheng and Du-66) and low activated extent of oil formation commonly existed (generally 50%), which not only seriously affect cyclic steam injection effectiveness, but also will exert great negative effects on the following steamflooding process.

Meanwhile, steamflooding encounts great difficulties. At one hand, the challenge of systemetic engineering integration must be overcomed, at the other hand, most of steamflooding pilots (totally 11 pilots) didn't obtain ideal effectiveness. The reservoir conditions greatly affect steamflooding performance. Only shu 1-7-5 block steamflooding pilot has been relatively good, the others, including the commercial steamflooding development in No 9 area of Karamayi oilfield in Xinjiang, have showed no ideal performance. Oil production rate after converting to steamflooding has been lower level, difficult to be restored, in some cases, too much lower compared with cyclic steam injection, OSR has also been lower, resulting poor economic benefit. By Sept. 1994, production wells of steam flooding in the whole country numbered 789, with average daily oil production per well only 2.0 t/d and annual average OSR 0.166.

Because the main driving force in the process of cyclic steaming is natural pressure energy in reservoir, and it will be exhausted, it is difficult for cyclic steaming to obtain high oil recovery and good ultimate development effectiveness. Enhancement of oil recovery must rely on effictive driving process. Therefore, cyclic steam injection must be effectively converted to steamflooding in order to greatly enhance the overall heavy oil development.

Effective conversion consists of two aspects. The first is, for heavy oil reservoirs suitable to steamflooding, favorable conditions should be created and cyclic steaming should be timely converted to steamflooding to enhance heavy oil recovery; the second, for heavy oil reservoirs not suitable or temporaryly not suitable to steamflooding, potential should be analysed and effective measures should be developed and taken to enhance cyclic steaming effectivess; at the same time, various conditions should be improved and technology advancement should be forwarded so that economically effective steamflooding can be implemented eventually for the heavy oil reservoirs temporaryly not suitable to steamflooding.

In this way, at present, what heavy oil reservoir is suitable to be converted to steamflooding and what are the favorable conditions for the conversion? That should be prerequisitely answered.

The influencing factors on steamflooding are complexe and various, including not only the geologcial conditions of the reservoir itself, but also production technique of cyclic steaming, development conditions and the technical management in the process of steamflooding. Especially in the case of complex geological conditions and strong heterogeneity for China heavy oil reservoirs (most continental deposits), many new problems and reservoir conditions variations occured after long time cyclic steam injection, such as low reproduction rate of injected steam, large differences of vertical activated extent of oil formation and serious steam channelling in cyclic steaming etc. It has been reconginized through steamflooding pilots that these factors can greatly influence steamflooding. Simply screening the reservoir geological conditions will not lead to practical criterion of steamflooding.

Therefore, in this paper, a comprehensive research approach has been adopted, that is, according to the geological conditions and production conditions in cyclic steaming and referencing the status of steamflooding pilots, both aspects of geological and production conditions are studied on the basis of three typical types of reservoirs (block, multi-layer and single sand body) using thermal recovery numerical simulation to comprehensively determine the screening criterion of steamflooding fittable to the present thermal recovery technical situation.

The studied geological conditions include oil viscosity, formation thickness, vertical permeability heterogeneity of formation, and production conditions include vertical activated extent of formation、channelling path、re-production rate of injected steam in cyclic steaming. Geological cross section schematic of three typical types of reservoirs are shown in fig. 2 and the studied items listed in table 1. Three dimensional, three phase、multi-component thermal recovery simulator was used.

The well pattern in the studies is inverted 9-spot pattern with spacing 100m (distance between injector and producer) which is adopted in most of heavy oil reservoirs at present. The basic geogical parameters and production parameters used in the studies are listed in table 2-3, and before steamflooding, the reservoirs had been cyclicly steamed several cycles with oil recovery between 10% to 18%.

RESERVOIR GEOLOGICAL CONDITIONS SUITABLE TO STEAMFLOODING

Effects of Oil Viscosity and Oil Formation Thickness.

In the process of steamflooding for heavy oil thermal recovery, oil viscosity and oil formation thickness are the very important factors influencing steamflooding performance. For example, if the oil viscosity is too high, up to 10^4 or 10^5 cp, and the oil formation is too thin, steamflooding these heavy oil reservoirs will hardly achieve good technical and economic results. The effects of oil viscosity and formation thickness have been studied at the three typical types of reservoirs as mentioned before. For block reservoir, the studied formation thickness include 15m, 25m, 45m and 60m; for multi-layer reservoir, 10m, 15m, 20 m and 30 m and for single sand body reservoir, 5m, 10m, 20m. At different formation thickness, various oil viscosities have been studied. They are 500cp, 2,000cp, 5,000cp, 10,000cp and 20,000cp at reservoir tempertature.

Research results (Fig. 3～6) indicate that the higher the oil viscosity and the smaller the formation thickness, the lower the steamflooding OSR. That is because, if oil viscosity is too high, injected steam can't effectively heat the oil to decrease its viscosity to the degree that oil can obtain good flow capacity, and for thin oil formation, the heating efficiency of injected steam is low because of large heat loss to the overburden and underburden. According to the present economical OSR limit (0. 15～0. 16), for the heavy oil reservoir feasible to steamflooding, its oil viscosity at reservoir temperature should be less than 10,000cp and oil formation thickness larger than 10m generally, in the case of multi-layer reservoir, larger than 15m since heat loss will be greater as the result of injected heat also transfered into the interbeded shales (Fig. 5).

In addition, for block reservoir, if oil formation is too thick, serious steam overide will lead to poor oil recovery (Fig. 4) because of strong gravity seperation of injected steam, therefore, too large thickness will not be appropriate and middle thick formation (<45m) is favorable.

Effects of Vertical Permeability Heterogeneity of Oil Formation

Vertical permeabilitg heterogeneity of oil formation can lead to steam injectivities different from layer to layer, resulting in early steam breakthrough in the high permeable layer, it can greatly affect steamflooding effectiveness in the way of decreasing sweep efficiency and lowering oil recovery.

In order to study its effects on steamflooding, permeabitily variation coefficient (or difference factor) has been used in this paper to describe the vertical permeability heterogeneity of oil formation, which is defined as

$$VPVC = \frac{\bar{K} - K_\delta}{\bar{K}}$$

where, VPVC—Permeability variation coeffient

$\bar{K}$—Permeabilty corresponding to 50% cummulative frequency. (Fig. 7)

K_δ—Permeability corresponding to 84% cumulative frequency. (Fig. 7)

and the definiation of permeability difference factor.

$$D_K = \frac{K_{max}}{K_{min}}$$

Where: D_K—Permeability difference factor.

K_{max}—The maximum permeability of layers.

K_{min}—The minimum permeability of layers.

Steamflooding at various VPH has been studied for three typical heavy oil reservoirs (as an example, VPH for block reservoir shown in table 4). The basic parameters are $h=45$ m and $\mu=5{,}000$ cp for block reservoir, $h=20$ m and $\mu o=2{,}000$ cp for multi-layer reservoir and $h=10$ m and $\mu o=2{,}000$ cp for single-sand-body reservoir. The results indicate that the stronger the VPH, the earlier the steam breakthrough and the less the sweep efficiency (Fig. 8). As VPH becomes strong, oil recovery will be evidently decreased (Fig. 9). Through comparison of simulated oil recovery with the estimated economical value (Fig. 10), it can be proposed that permeability variation coefficient less than 0. 6 would be favorable for steamflooding, the corresponding pemeability difference factor value is less than 10.

PRODUCTION CONDITIONS SUITABLE TO STEAMFLOODING

Effects of Activated Extent of Oil Formation

Activated extent of oil formation means the ratio of effective producing intervals thickness accounting in the gross thickness put into production. According to the statistical data of Liaohe oilfield, the average AEOF for its total heavy oil reservoirs is only about 47%. In Xinjiang oilfield, the thickness of main steam absorbing layers only accounts for 40% of gross thickness of oil formation. In fact, AEOF indicates the vertical sweeping status of injected steam. To investigate its effects on steamflooding, numerical simulation has been carried on in three typical reservoir models. The basic parameters (oil viscosity and oil formation thickness) of these models are the same as the above.

From the simulation results (Table 5), it can be seen that as AEOF lowers, the effectiveness of steamflooding becomes poor, i. e., oil recovery decreases. Its effects are particularly evident for mulit-layer reservoir, while AEOF is less than 50%, steamflooding OSR will be lower than 0. 16. If there are no effective measures to improve AEOF in the process of steamflooding, effective steamflooding will be hardly implemented. Considering the economical limit of ORS (0. 15~0. 16), for heavy oil reservoirs suitable to steamflooding, AEOF should be not below 50%.

Effects of Channelling Path Formed In Cyclic Steaming

At Karamayi oilfield in Xinjiang, Shajiashi oilfield in Shengli and some areas in Liaohe, serious steam channelling occured generally in cyclic steam injection. In the process of enlarged steamflooding at Karamayi No. 9 district, steam channelling is also prominent. In that way, how does channelling path affect steamflooding if it has been formed in the reservoir through several steaming cycles?

Single sand body model has been used to study this matter. Thickness of sand body is 10m, with 2m shales interspersed in sand body. Channelling path is represented by a regional very thin layer in the middlle of oil formation.

As shown in table 6, the results indicate that the oil recovery and OSR of steamflooding are decreased 51% and 39% respectively by the channelling path existing in reservoir. Channelling path formed in cyclic steaming greatly affects steamflooding performance, displaying as low oil production of 1～2 months, shortly increasing, greatly declining and hardly to be restored (Fig. 11). Liguid production (Fig. 12) greatly increases in short time and wellhead temperature rapidly goes up, 30～40℃ higher than that of no-channelling path. It is analysed that the existing channelling path leads steam channelling in the path, resulting in great amount of steam be produced, only the oil in and near the path be brought along steam. Although liquid production increases greatly, oil production decreases sharply and steamflooding is very poor.

Therefore, in the case of strong channelling path existing in reservoir and if there is no effective controlling measure, steamflooding will not be feasible to that reservoir.

Effects of Re-Production Rate of Injected Steam

The problem of low re-production rate of injected steam occured in some of heavy oil reservoirs in China in the process of cyclic steam injection, for example, Gaosheng oilfield and Du-66 block demonstrate RPRIS only 15% (RPRIS means the ratio of quantity of produced water to that of injected cold water-equivalent steam). The reasons of this problem are complex, many aspect and not totally known. By far, according to the analysis, the possible reasons may include the following aspects: more water-wettability of rock at high temperature condition; oil emulsion and blocking; swelling of clay minerals, especially the new minerals generated at high temperature (mainly smectite); production problems. Low RPRIS indicates poor flowing ability of the liquid in reservoir, leading to both oil and water production being low level. Deepening discussion of the reasons does not belong to the scope of this paper. What this paper is investigating is just its effects on steamflooding.

The block reservoir and multi-layer reservoir models have been used for this study and the parameters of oil viscosity and formation thickness are also as the same as before.

The studied results indicate that as RPRIS decreases, both oil recovery and OSR go down (Fig. 13), and the peak production appearence in steamflooding is defered and low production period prolonged (Fig. 14). If RPRIS is too much low, steamflooding will be at long-time low production and lost the peak production. For the mechanisms, RPRIS can exert great influence on water saturation and reservoir pressure distributions at the end of cyclic steaming, also the steam saturation field in the process of steamflooding (Fig. 15～17). At low RPRIS situation, after converting to steamflooding, the swept regions by injected steam are limited, sweep efficiency decreased because of higher reservoir pressure; moreover, because of much injected water existing in formation, some amount of heat of injected steam is exhausted to heat the existing water, resulting in steam front forwarding slowly (Fig. 17). In view of economical limit of OSR 0.15～0.16 in steamflooding, RPRIS should be not below 35～40% for the reservoirs suitable to steamflooding.

CONCLUSIONS

Based on the above studies and referencing present steamflooding screening standard (table 7, ref. 3), this papar proposes a comprehensive steamflooding screening criterion, which has taken the present production technique and development conditions as evaluation bases (table 8). For the reservoirs feasible to steamflooding at present, the main points can be summarized as:

1. Oil viscosity and oil formation thickness are important factors for steamflooding. Oil viscosity should be less than 10,000cp; Generally, oil formation thickness should be greater than 10m, specificly for multi-layer reservoirs greater than 15, meanwhile, it is also not suitable for formation thickness to be too thick and middle thickness less than 45m would be favorable.

2. Vertical permeability heterogeneity of oil formation may greatly influence steamflooding effectiveness. The stronger it is , the largerly the oil recovery decreases. The favorable vertical permeability variation coefficient should be no more than 0. 60, correspodent vertical permeablity difference factor less than 10.

3. Lower oil formation activated extent corresponds to reduction of flooded thickness by steam, resulting in steamflooding effectiveness becoming poor. Within the thickness limit, oil formation activated extent should be higher than 50%.

4. The existing channelling path formed in cyclic steaming can exert harmful effets on steamflooding, that is , steamflooding oil recovery and OSR may be greatly decreased. If no effective controlling measures to be taken, steamflooding is not suitable.

5. Re-production rate of injected steam in cyclic steaming can obviously affect steamflooding. Low re-production rate of injected steam results in abundance of water existing near the well and in turn lowers heating efficiency in the driving process, and the performance would be poor after converting to steamflooding. The fittable re-production rate of injected steam in cyclic steaming should be no less than 35～40%.

6. The above conclusions are just based on present production technique and development conditiions, and they are relative. As advancement of production technique and adjustment of development system, the scope of heavy oil reservoirs feasible to steamflooding will be enlarged. and this screening criterion can be further revised for more perfection. In addition, they are also general, for particular reservoirs, some modifications might be necessary.

ACKNOWLEDGMENT

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Table 1 The Studied Items and Contents

Conditions	Items	Type of Reservoirs			Contents
		Block	Multi-Layer	Single Sand Bady	
Geological	Oil Viscosity, cp.	√	√	√	500,2000,5000,20000
	Oil Formation Thickness, m	√	√	√	5,10,15,20,25,45,60
	Vertical Permeability Heterogenelty	√	√	√	VPVC = 0, 0.15, 0.3, 0.45, 0.55, 0.65, 0.75, 0.85
Production	Vertical Activated Extent of Oil Fomation	√	√	√	1/4,1/3,1/2,1
	Channelling Path In Reservoir			√	
	Re-Production Rate of Injected Steam in Cyclic Steaming	√	√		High, Middle, Low

Note: Oil viscosity is at reservoir temperature. √ means the items were studied.

Table 2 The Basic Reservoir Parameters

Geological parameters	Type of Reservoirs		
	Block	Multi-Layer	Single and body
Buried Depth, m	1200	1200	400
Ratio of Net/Gross Thickness	1.0	0.5	0.8
Permeability, md	2000	800	2500
Porosity, %	25.0	26.0	32.0
Oil Saturation, %	65.0	65.0	65.0
Initial Reservoir Pressure, MPa	12.0	12.0	4.0
Reservoir Temperature, ℃	50.0	55.4	24.9

Table 3 Production Parameters of Steam Injection

Production Parameters	Types of Reservoirs		
	Block	Multi-Layer	Single Sand Body
At Cyclic Steam Injection			
Injecting Intensity, (t/m)	80	80	80
Injecting Rate, (t/d)	200	200	50～100
Wellbore Pressure, (MPa)	16.0	16.0	6.0
Wellbore Temperature, (℃)	340	340	270
Wellbore Steam Quality, (%)	40.0	40.0	60.0
At Steamflooding			
Injecting Rate, (t/d)	160	140	60
Injecting Pressure at Wellbore, MPa	16.0	16.0	6.0
Wellbore Steam Quality, (%)	40.0	40.0	70.0

Table 4 Vertical Permeability Distribution for Block Type of Heavy Oil Reservoir

Layer	Vertical Permeability Distribution, md				
	VPVC=0 (D_K=1.0)	VPVC=0.3 (D_K=2.8)	VPVC=0.45 (D_K=4.47)	VPVC=0.65 (D_K=14.5)	VPVC=0.85 (D_K=122)
1	2000	2000	2000	2000	2000
2	2000	3400	4200	7350	22000
3	2000	2400	2750	3500	5500
4	2000	1650	1500	1200	730
5	2000	1200	940	525	180

Table 5 Effects of Vertical Activated Extent of Oil Formation on Steamflooding

Types of Reservoirs	VAEOF, %	Time, d	Daily Oil Production of Single Well, t/d	OSR	Oil Recovery, %
Block	100	2760	12.5	0.234	17.6
	50	2960	11.6	0.217	17.5
	33	3124	10.9	0.204	17.3
	25	3260	10.6	0.198	17.3
Multi-Layer	100	1243	9.2	0.198	21.5
	50	1078	7.8	0.167	15.7
	33	765	7.3	0.156	10.4
	25	760	6.6	0.14	9.4
Single Sand Body	100	1579	5.0	0.252	20.1
	50	1726	4.2	0.210	18.9
	33	1765	3.9	0.196	18.0
	25	1783	3.8	0.188	17.5

Table 6 Effects of Channelling Path Formed in Cyclic Steaming on Steamflooding

Indexes	Channelling Path	No Channelling Path
Driving time, Day	1200	980
Daily Oil Production of Single Well, t/d	3.9	2.4
Oil-Steam Ratio	0.196	0.120
Oil Recovery, %	20.08	9.91

Table 7 Steam Flooding Sieving Criterion and Heavy Oil Reserve Classification Criterion

Parameter group	First class on available technology	Second class on technology improvement in recent period	Third class waiting for technology development	Fourth class not suitable for steam-injection recovery
1. Crude viscosity (at reservoir T)	>50—10000	<50000	<50000	
Gravity	<0.95	<0.95	<0.98	
2. Formation depth, on	<1400	<1600	<1800	
3. Net thickness of Pay	⩾10	⩾10	⩾5	⩾5.0
Net/Total thickness ratio	>0.50	>0.50	>0.50	>0.5
4. Φ	>0.20	>0.20	>0.20	>0.20
Soi	>0.50	>0.50	>0.40	>0.40
Φ×Soi	⩾0.10	⩾0.10	⩾0.08	⩾0.08
Reserve factor IOMT/kmk^2 · m	>10.0	>7.0	>7.0	>7.0
5. Permeability (md)	⩾250	⩾250	⩾200	⩾200

Table 8 Feasible Steamflooding Screening Criterion Based on Present Thermal Recovery Technical Situation

Group I Geological Conditions	Parameters
1. Oil viscsity, cp	<10000
Gravity, g/cm^3	<0.95
2. Formation Depth, m	<1400
3. Oil Formation Thickness, m	⩾10(>15 for multi-Layer Reservoir) <45
Net/Gross Thickness Ratio	>0.5
4. Φ	>0.2
Soi	>0.5
Φ×Soi	>0.1
5. Permeability, md	>250
Vertical Permeability Variation Coefficient	<0.6

Group I Production Conditions	Parameters
1. Activated Extent of Oil Formation	>50%
2. Channelling Path in Reservoir	No or Little Function
3. Re-Production Rate of Injeccted Steam (Water)	>35～40%

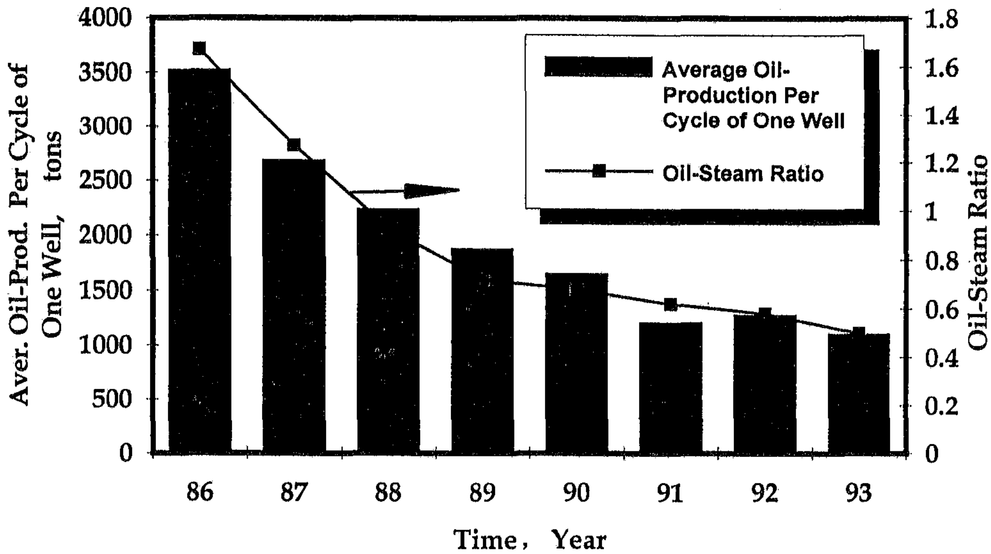


Figure 1 OSR and Oil-Production Declining Curve from 1986 to 1993

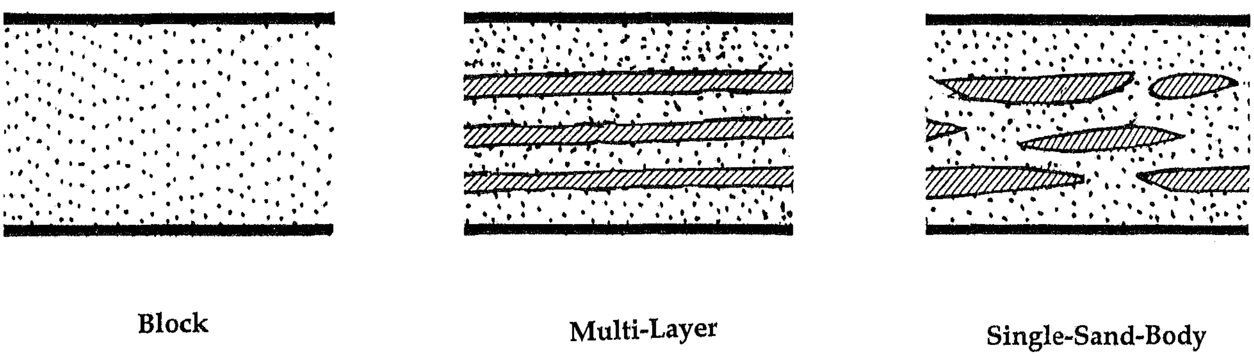


Figure 2 Schematic of Three Typical Heavy Oil Reservoir in China

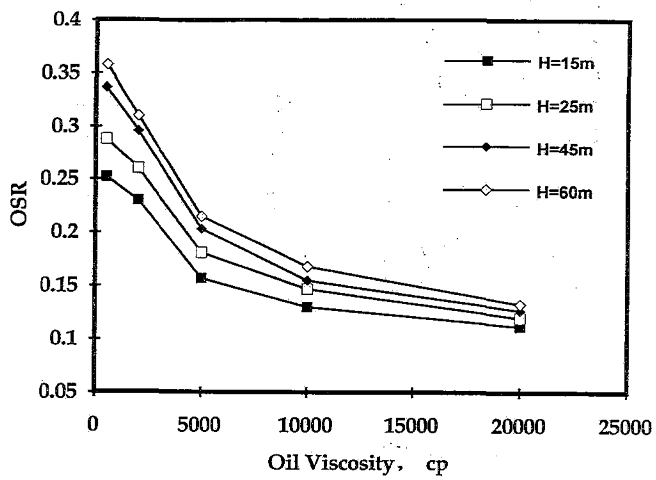


Figure 3 Steamflooding OSR vs. Oil Viscosity and Oil Formation Thickness for Block Type Heavy Oil Reservoir

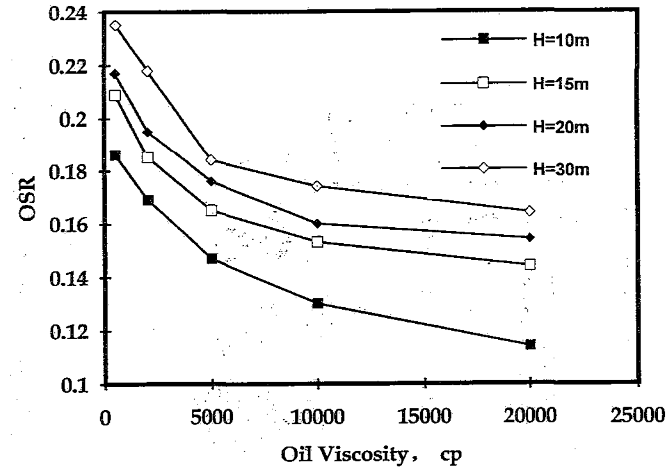


Figure 5 Steamflooding OSR vs. Oil Viscosity and Oil Formation Thickness for Multi-Layer Type Heavy Oil Reservoir

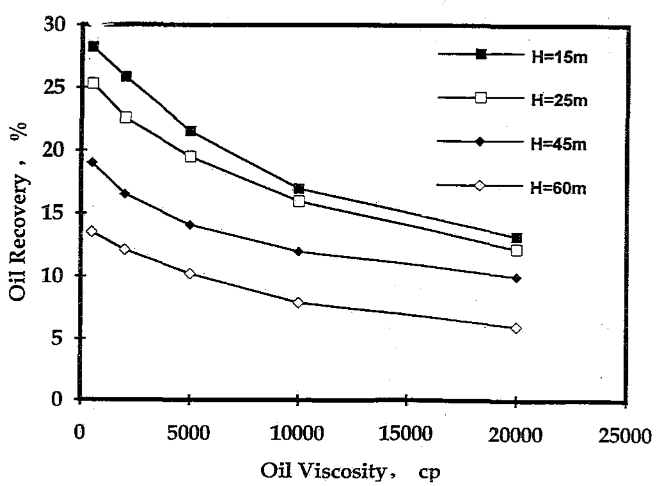


Figure 4 Steamflooding Oil Recovery vs. Oil Viscosity and Oil Formation Thickness for Block Type Heavy Oil Reservoir

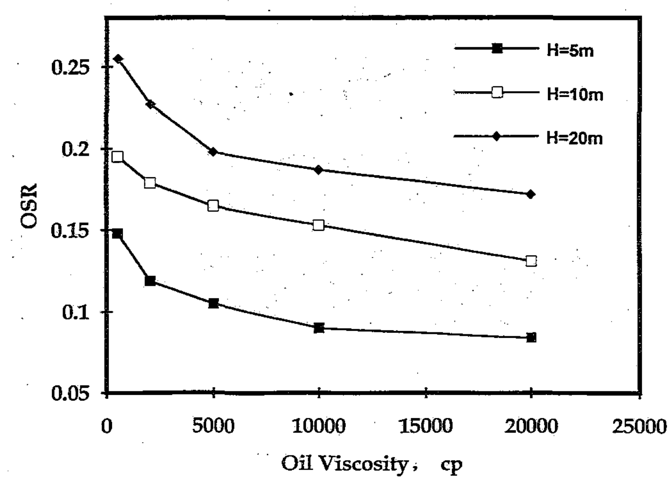


Figure 6 Steamflooding OSR vs. Oil Viscosity and Oil Formation Thickness for Single-Sand-Body Type Heavy Oil Reservoir

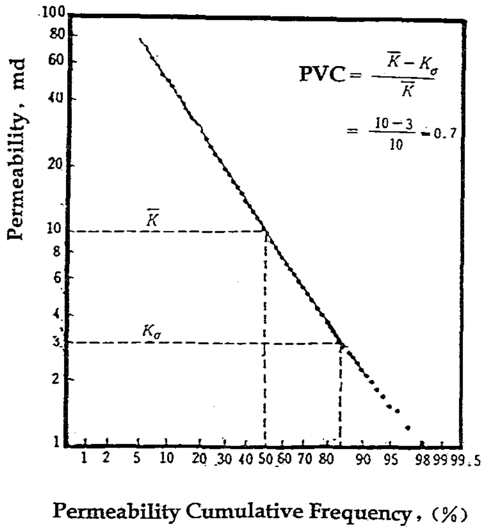


Figure 7 Permeability Lognormal Cumulative Frequency Plot

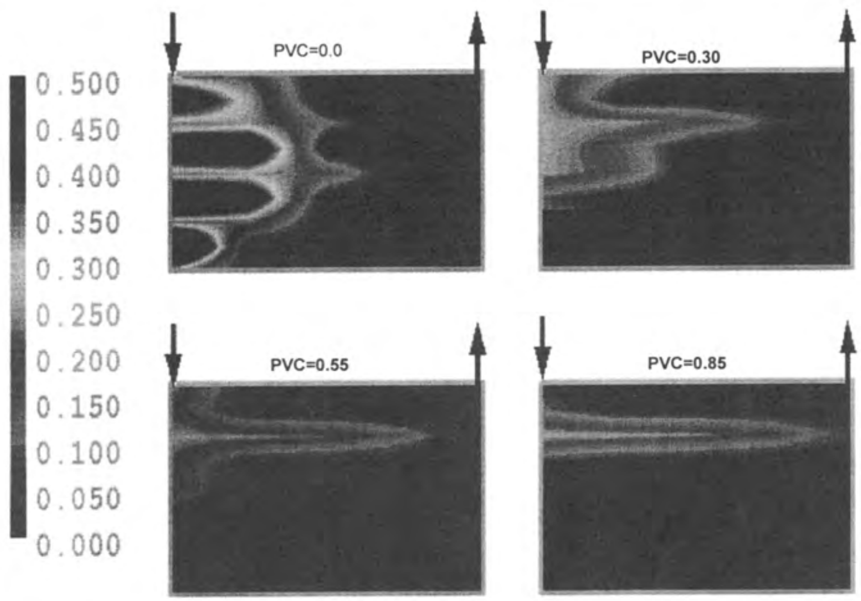


Figure 8 Steam Saturation Field at Different PVC in Steamflooding for Block Multi-Layer Heay Oil Reservoir (T=1400Days)

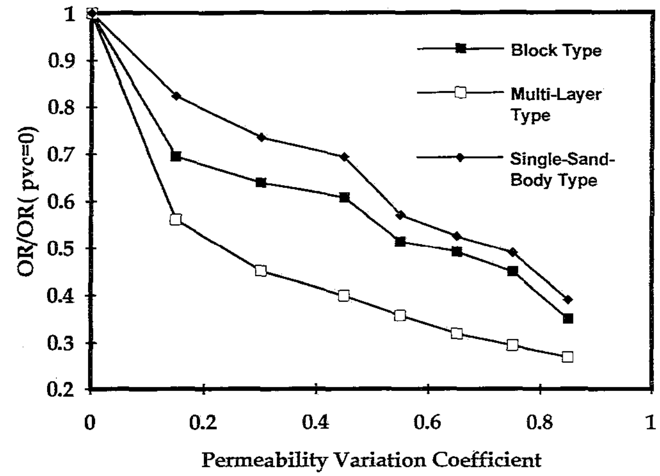


Figure 9 Effects of Vertical Permeability Varation Coefficient on Steamflooding Oil Recovery

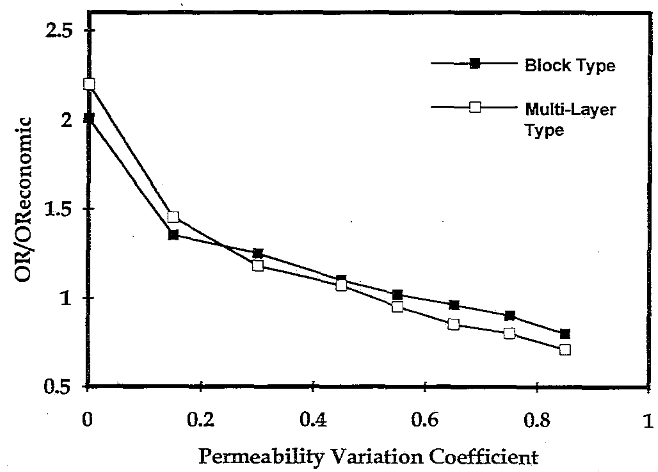


Figure 10 Effects of Vertical Permeability Varation Coefficient on Steamflooding Oil Recovery

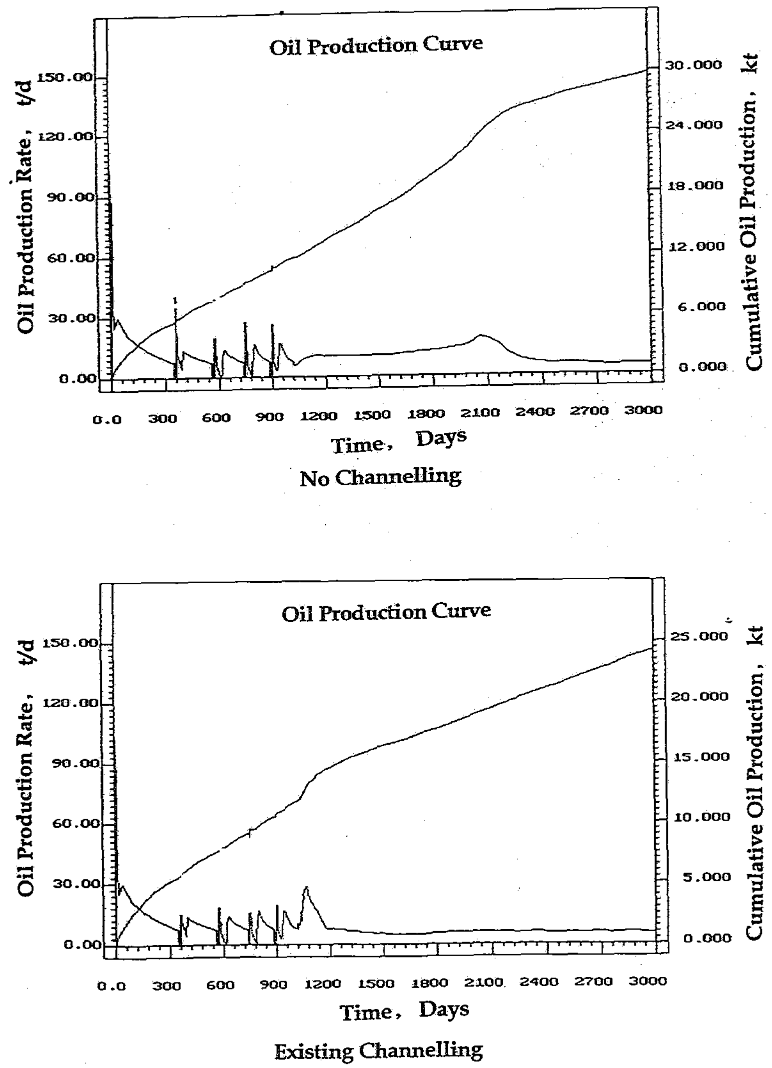


Figure 11 Oil Production Curve for Influence of Channelling

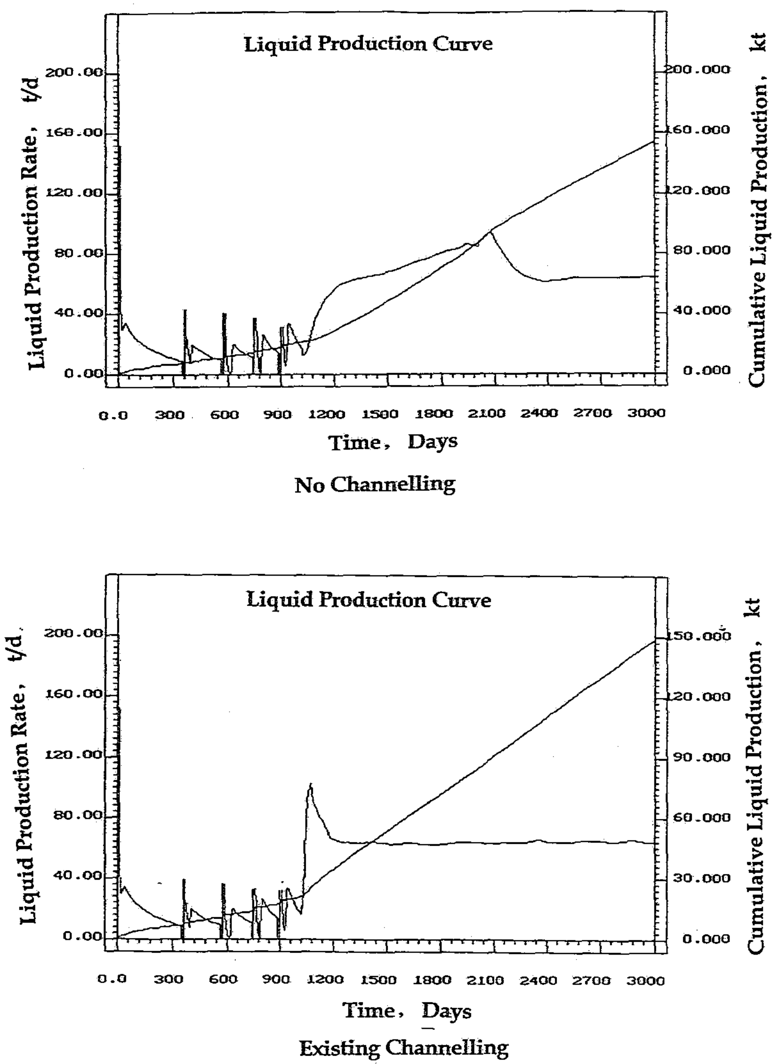
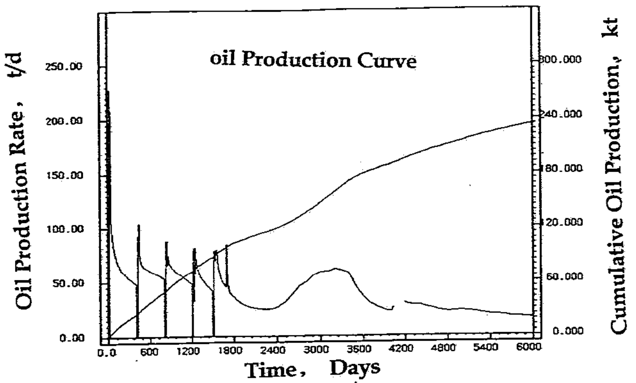
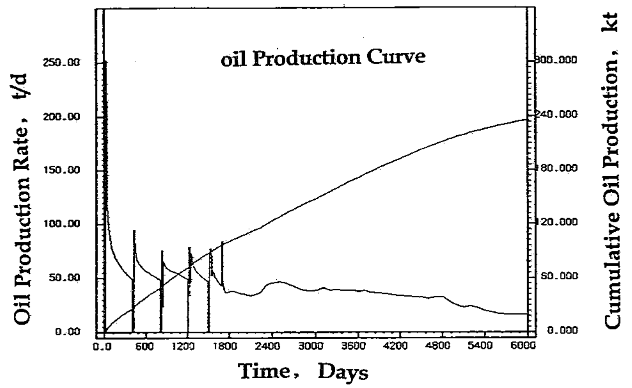


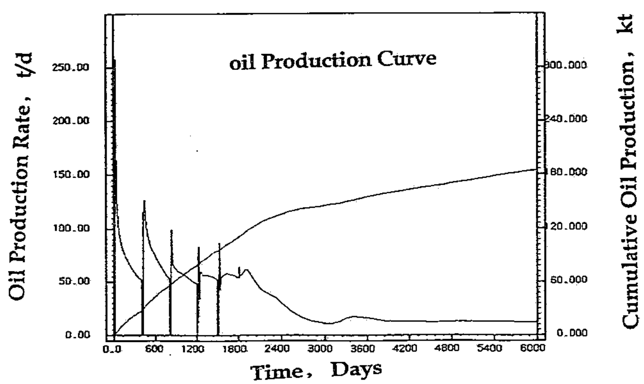
Figure 12 Liquid Production Curve for Influence of Channelling



Hight Re-Preduction Rate of Injected Steam

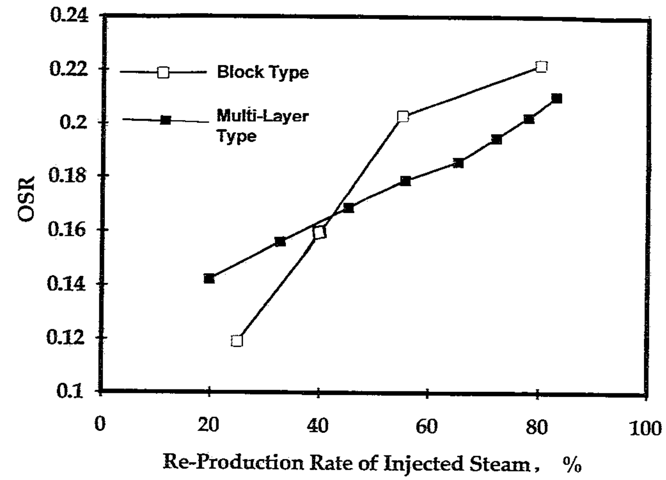


Middle Re-Preduction Rate of Injected Steam



Low Re-Preduction Rate of Injected Steam

Figure 13 Oil Production Curve for Different Re-Preduction Rate of Injected Steam at the End of Cycling



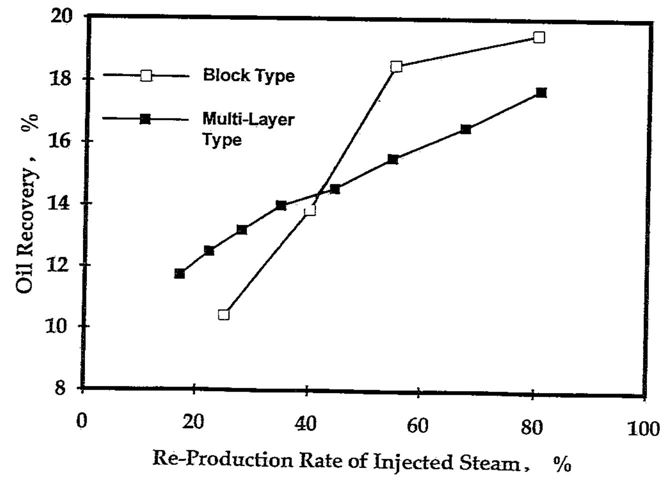


Figure 14 Effects of Re-Production Rate of Injected Steam on Steamflooding OSR and Oil Recovery

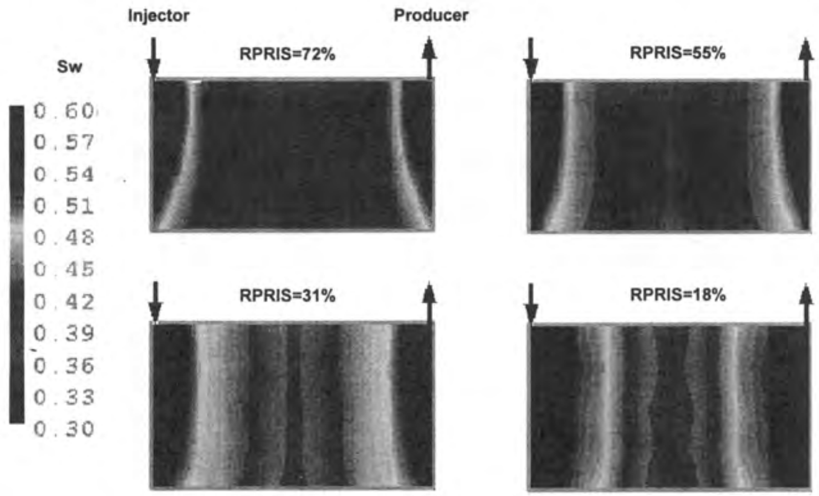


Figure 15 Water Saturation Distribution at End of Cyclic Steaming at Different Re-Production Rate of Injected Steam

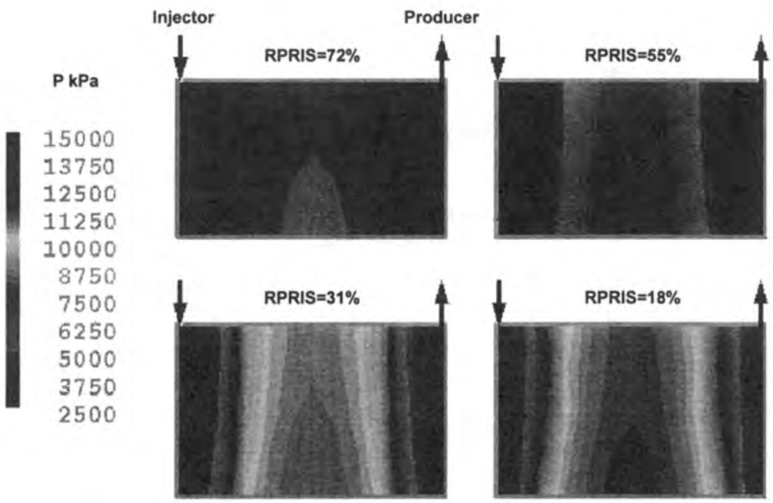


Figure 16 Pressure Field at End of Cyclic Steaming at Different Re-Production Rate of Injected Steam

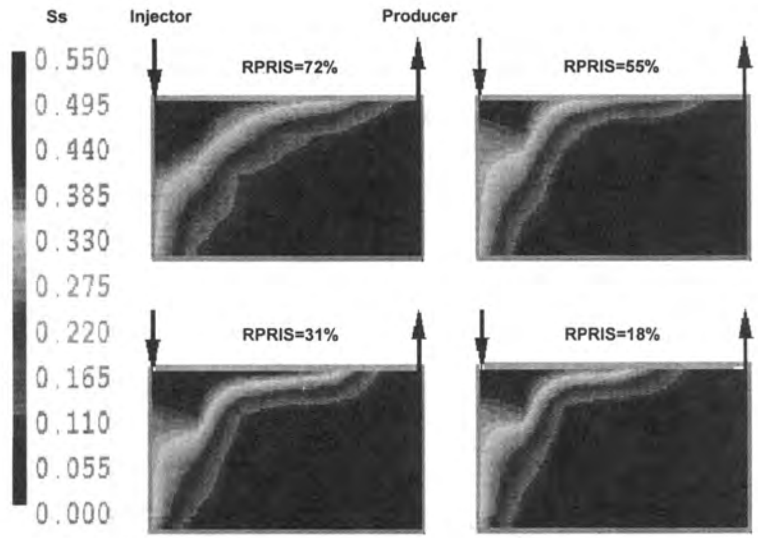


Figure 17 Steam Saturation Field at Different Re-Production Rate of Injected Steam in Steamflooding (T=1120 Days)